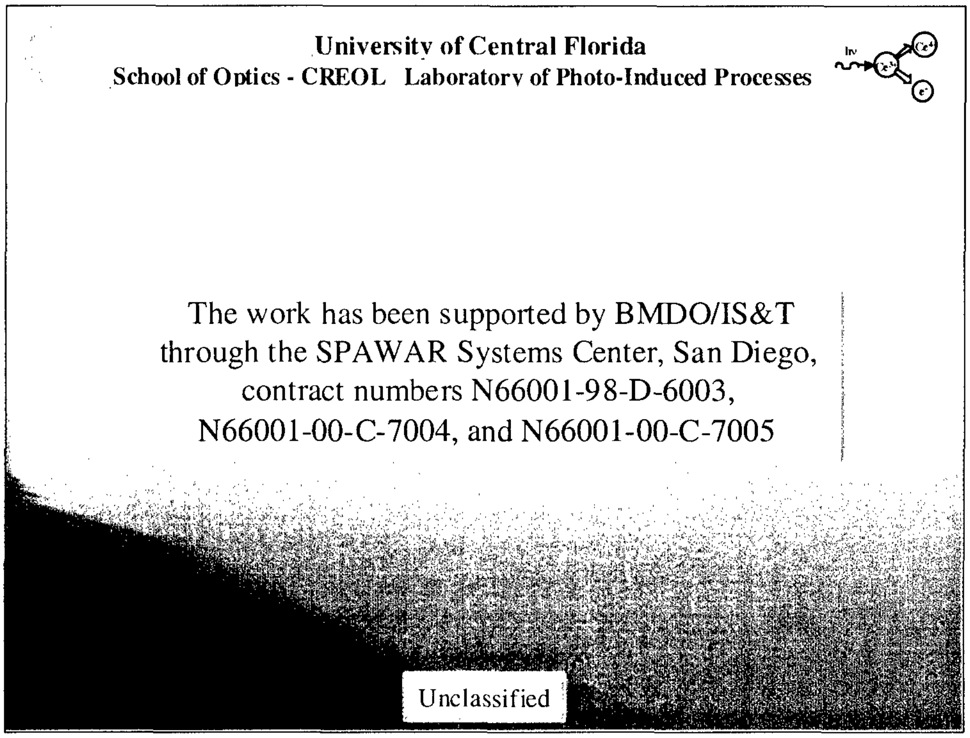
TITLE: A New Approach to Rugged Optical Components With High Spectral and Angular Selectivity

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

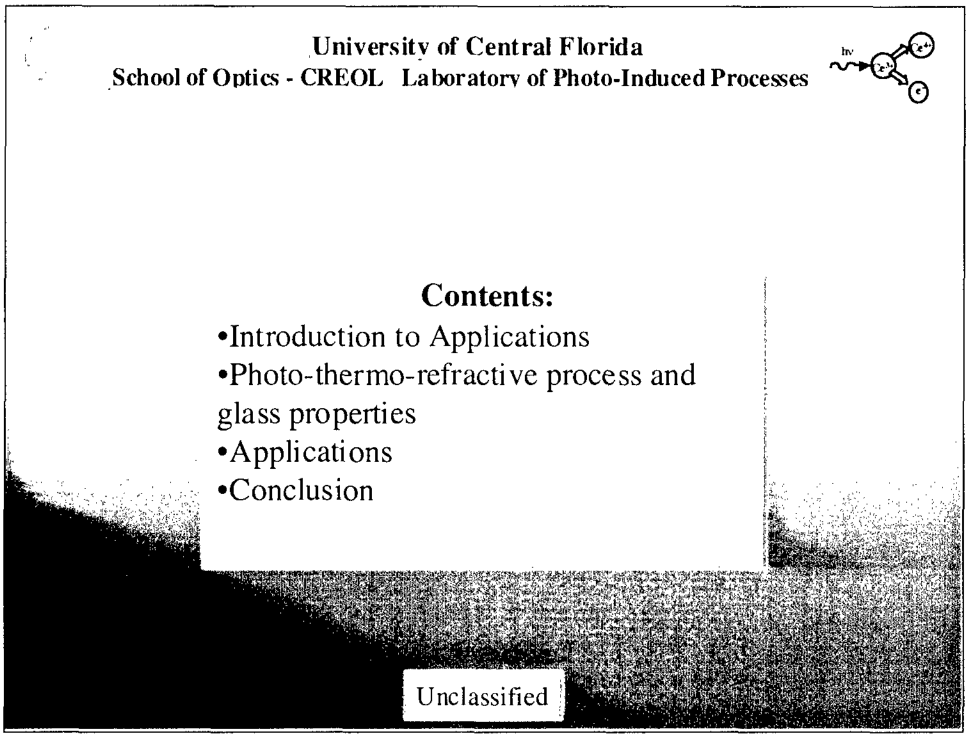
A NEW APPROACH TO RUGGED OPTICAL COMPONENTS WITH HIGH SPECTRAL AND ANGULAR SELECTIVITY

L.B. Glebov, and C.M. Stickley
School of Optics/CREOL
University of Central Florida, Orlando, FL 32816-2700
O.M. Efimov,
Light Processing and Technologies, Inc. Orlando, FL 32817

This is a report on a new materials technology, PTR glass, which will make possible rugged, lower cost, light weight optical components having wide application to both low-power and high-power laser systems. Applications we forsee include: both spectral and angular beam steering and beam scanning, high resolution beam filtering, reflecting, transmitting, splitting, beam combining, and correcting of aberrations in telescopes and other optical systems. This PTR glass and some of these components are being produced at CREOL. I shall report our results to date in achieving these applications.



This work was initiated at CREOL/UCF by BMDO support in 1996 and has received BMDO support since then through SPAWAR Systems Center, San Diego. The success of this research program has led to support by BMDO of two STTR projects with Light Processing and Technologies, Inc.; these were directed toward development of particular diffractive components and commercialization of the technology.

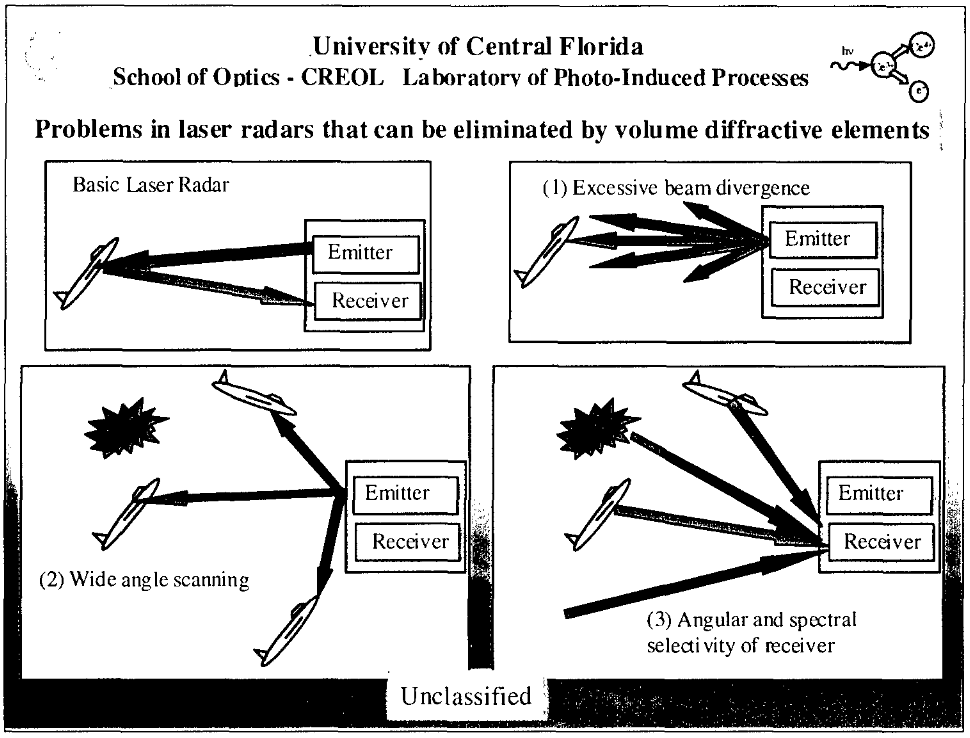


In this presentation we will discuss the general needs for diffractive components in optical systems designed for targeting and surveillance and for high energy lasers. Then we will explain the basis of the photo-thermo-refractive technology for phase pattern recording in the volume of optical glass. After this, we will describe optical properties of photo-thermo-refractive (PTR) glass which are currently achieved and show the properties of different Bragg gratings recorded in those glasses. Later we will show a survey of possible applications of those new optical components and demonstrate the first experimental results.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

INTRODUCTION TO APPLICATIONS

Unclassified



Optical systems designed for targeting and surveillance can work in a passive or active mode. A great number of optical and electronic components are necessary for providing the proper operation capability of these systems. There are several problems in the design of the transmitters and receivers that could be solved with the diffractive optical components. The first problem is excessive divergence the laser transmitter. The conventional systems that provide single mode, diffraction limited operation are usually very bulky and heavy. A simple, low mass and weight approach to this is to use thick Bragg gratings in PTR glass within the cavity of a laser to produce near diffraction limited operation. Another problem is beam scanning. Conventional devices have angular ranges of scanning that are less than 100 mrad (5 degrees) while 180 degrees should be covered by the scanning beam. By a matrix of Bragg gratings in PTR glass, angular magnification and thus scanning of the beam can be achieved. [Spectral scanning may also be achieved]. The third problem is the angular and spectral selection of the receiver in conditions of the high background light levels. PTR glass can be used to make highly wavelength and angle-selective, volume-diffractive mirrors for installation in the receiving telescopes, thus leading to a low cost, high performance improvement in such systems.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Volume gratings in PTR glass will enable rugged, low cost, insensitive optics for high energy lasers:

- **Reflectors**
- **Beam splitters and attenuators**
- **Mode selectors**
- **Beam combiners**

Unclassified

We believe that many problems with optics in high energy or high power lasers could be solved with PTR glass. The components that can be made with this rugged glass are shown on the viewgraph: reflectors, beam splitters, attenuators, mode selectors, and beam combiners.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Fixed aberrations in optical systems can also be eliminated:

- **Measure wavefront distortion of beam propagating through the system**
- **then make the phase conjugate of this aberration using the PTR process**
- **insert it into optical system to permanently correct it**

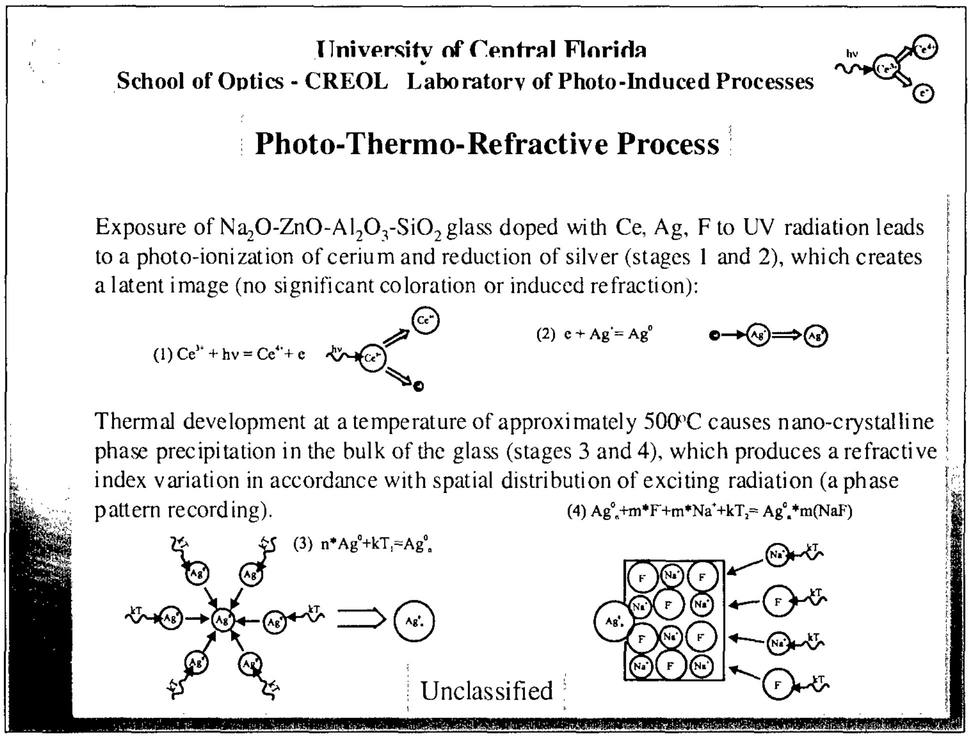
Unclassified

The third major application of PTR glass is for correction of fixed aberrations or phase nonuniformities in optical systems. This technology should enable an optical system manufacturer to correct the fixed errors in his optical system as a final step in the system manufacturing process. Such optical systems include telescopes, cameras, imaging systems, and the Hubble telescope.

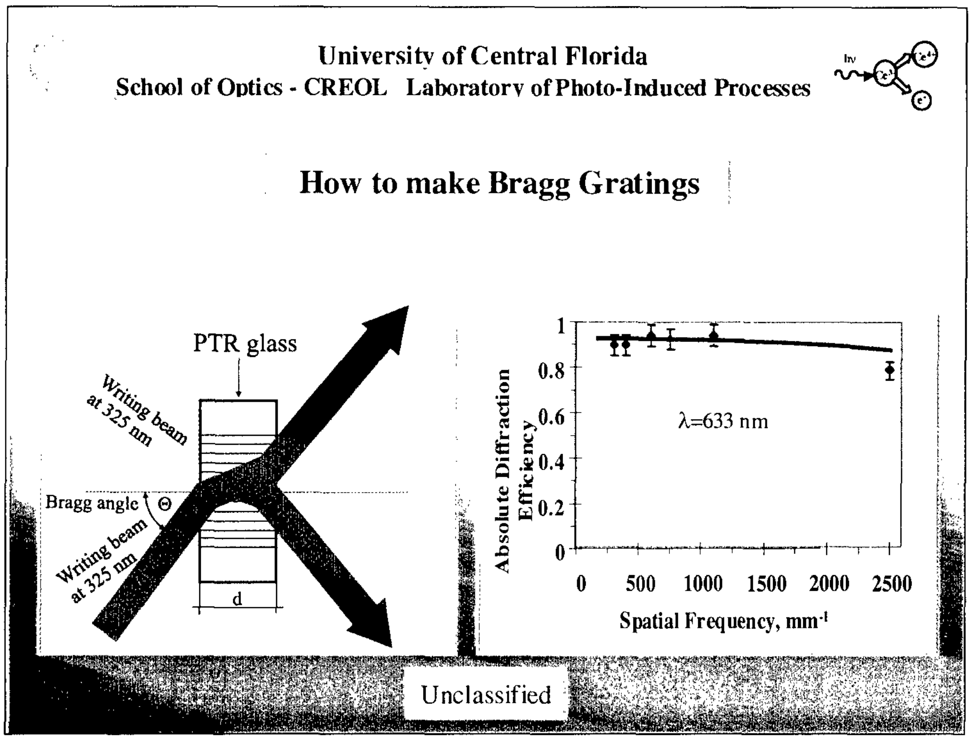
University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Photo-Thermo-Refractive Process and Glass Properties

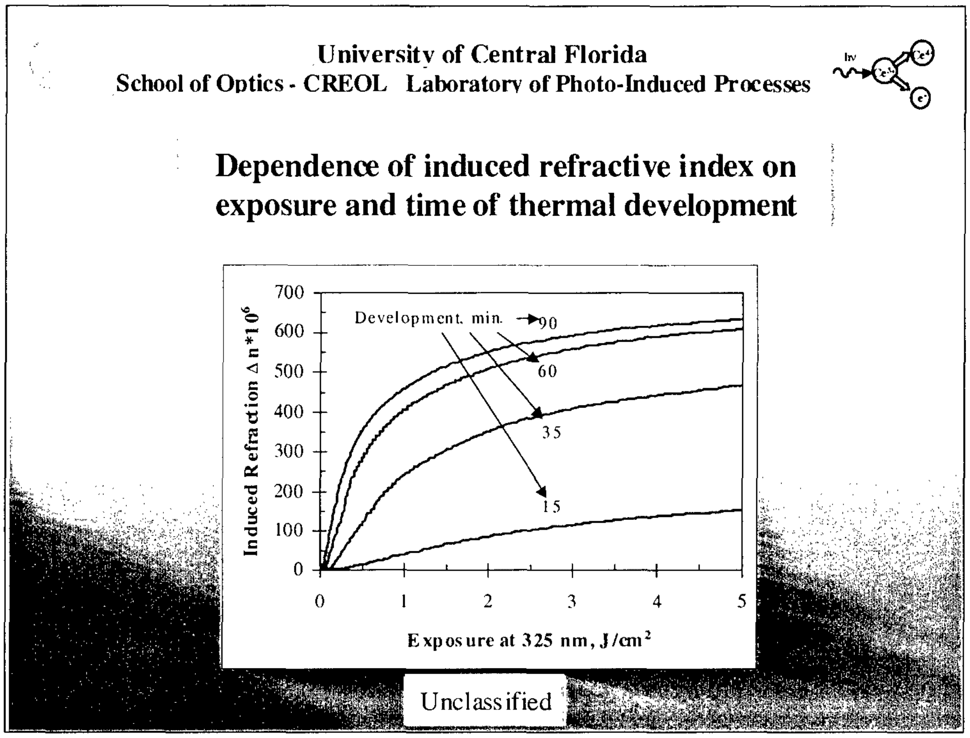
Unclassified



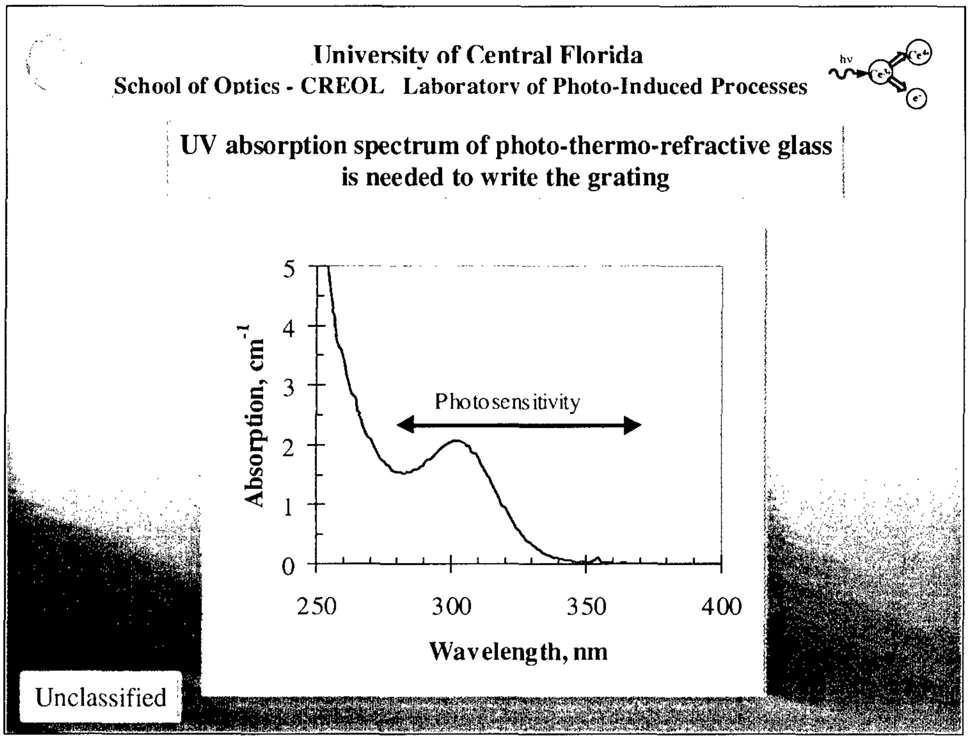
The photo-thermal process is based on precipitation of dielectric microcrystals in the bulk of glass exposed to UV radiation. The first step is the exposure of the glass sample to the near UV radiation, which produces an ionization of a cerium ion. The electrons released from the cerium are then trapped by a silver ion converting it to a neutral atom. This second stage corresponds to a latent image formation in conventional photomaterials. No significant coloration or refractive index variations occurs in PTR glass at this stage. The third stage is the diffusion of silver atoms, which leads to creation of tiny transparent silver crystals (colloidal particles) at temperatures of 450-500°C. These silver particles serve as the nucleation centers for sodium fluoride crystal growth at temperatures between 500°C and 550°C. It was found that after this stage, the refractive index of the exposed area decreases by about 10^{-3}. The phase pattern produced by precipitation of such nanocrystals is a thermodynamically stable one and cannot be erased before the matrix material (silicate glass) loses its stability (400°C in this case)..



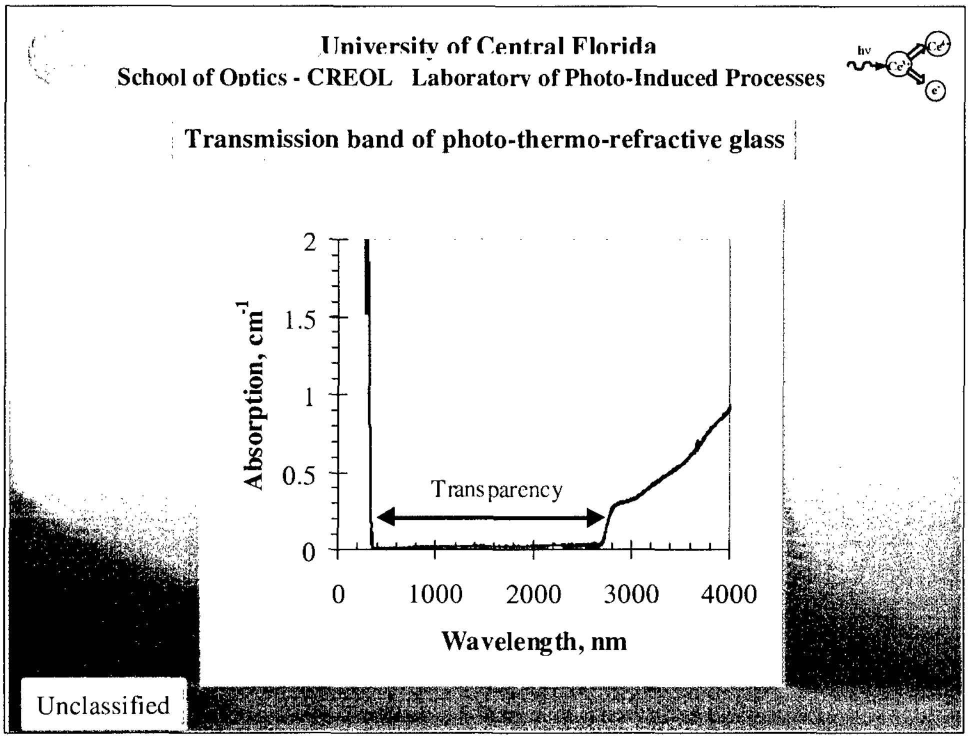
Bragg gratings in PTR glass are recorded by exposure to the interference pattern of radiation of a He-Cd laser operating at 325 nm with average power of 35 mW and are then fixed by heat treatment at 520°C. The spatial frequency of the grating has been varied from 200 mm^{-1} up to about 10,000 mm^{-1}. Volume gratings in both the transmitting and reflecting modes were recorded with thickness' ranging from 0.5 mm to 3 mm. The maximum aperture of the gratings was up to 12 mm×12 mm. The diffraction efficiency was measured at 633 nm, 1064 nm, and 1550 nm. In all cases, the maximum diffraction efficiency of these PTR Bragg gratings exceeded 90 % of the theoretical value.



The dependence of the induced index of refraction on dosage for different times of thermal development is shown in this figure. The induced refractive index exhibits a curve with a continuously decreasing slope. One can see that increasing the time of development increases the initial amplitude of the induced refractive index change which means increasing the actual photosensitivity. However, further development leads to the saturation of the induced index of refraction. This result allows tradeoffs to be made between exposure time and development time. It was found that there is no difference in the refractive index decrement for the different values of irradiance. This means that PTR glass obeys the Reciprocity Law and the induced index of refraction depends on the total dosage only. The maximum value of the refractive index increment in our experiments was about 10^{-3}. The refractive index decrement depends linearly on dosage up to $3 \cdot 10^{-4}$. An approximate value of the photosensitivity of PTR glass for 325 nm irradiation followed by 3 hours of development at 520°C is 1.5×10^{-3} cm^2/J.



The UV absorption spectra of PTR glass is presented in this figure. The absorption band of Ce^{3+} having a maximum at 305 nm is clearly seen. Photoionization of Ce^{3+} triggers the chain of photoinduced processes in PTR glass resulting in precipitation of NaF microcrystals. It is important to note that NaF is a high-bandgap dielectric material that has no absorption in the UV, visible, and near-to-mid IR regions

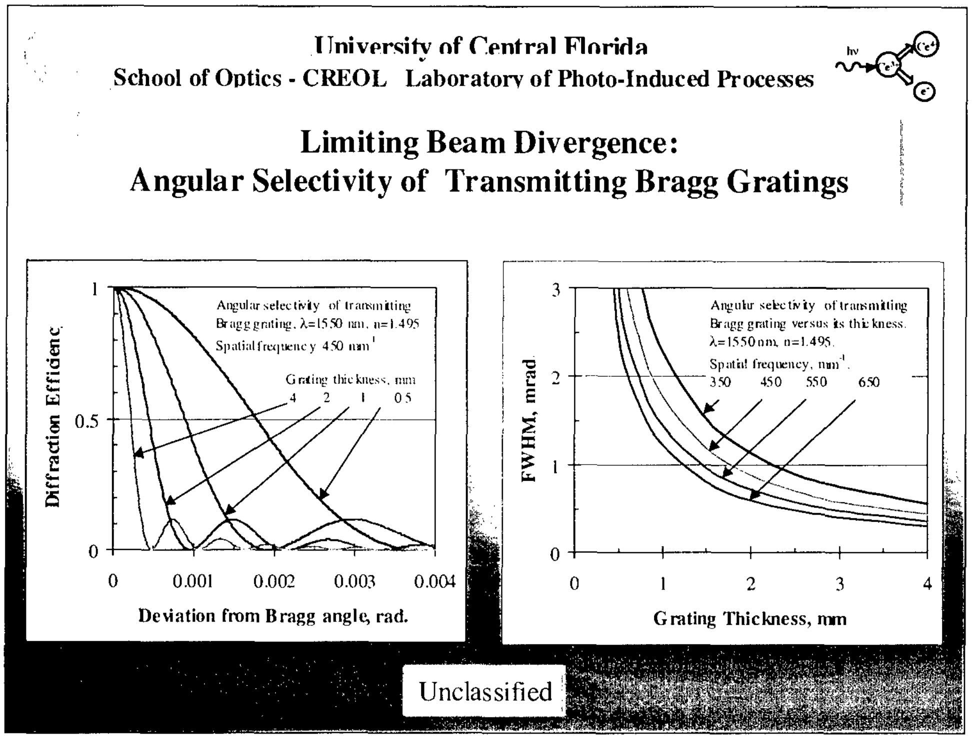


The window of transparency of PTR glass extends from about 300nm to 4000 nm. The UV absorption edge is attributed to Ce^{4+} and Ag^{+} contained in the glass. Absorption in the IR end of the spectrum is the absorption of water hydroxyl groups) and can be decreased by the development of dry glass melting technology. Absorption in the visible and near IR regions are caused by different impurities and can be controlled by the use of purified chemicals and the proper technology for glass fabrication. Additional absorption in the whole IR region is not detectable by a spectrophotometer. Consequently, diffractive optical elements made from PTR glass can be successfully used at all wavelengths in the visible and near IR regions important for military lasers and optical communication.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

APPLICATIONS

Unclassified

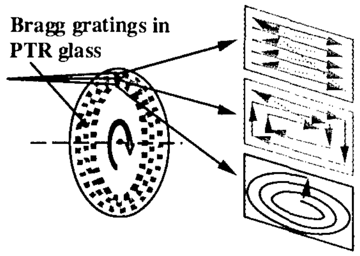


These curves illustrate the angular selectivity of the volume grating filters at 1550 nm. For angular filters, the transmission band becomes narrower as the thickness increases. For example, for a 4 mm thick grating, the full angular width is about 0.6 milliradian. The angular selectivity of the Bragg gratings produced in PTR glasses could be varied from about 100 μrad to 100 mrad depending on the spatial frequency and the thickness. In experiments, the angular selectivity of the transmitting PTR grating was about 10 % above the theoretical value. This means high homogeneity is achieved in the PTR glass slab.

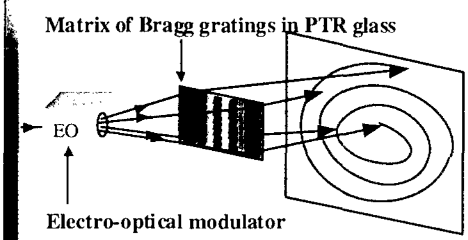
University of Central Florida

School of Optics - CREOL Laboratory of Photo-Induced Processes

Steering Agile Beams (STAB): Angular Magnification



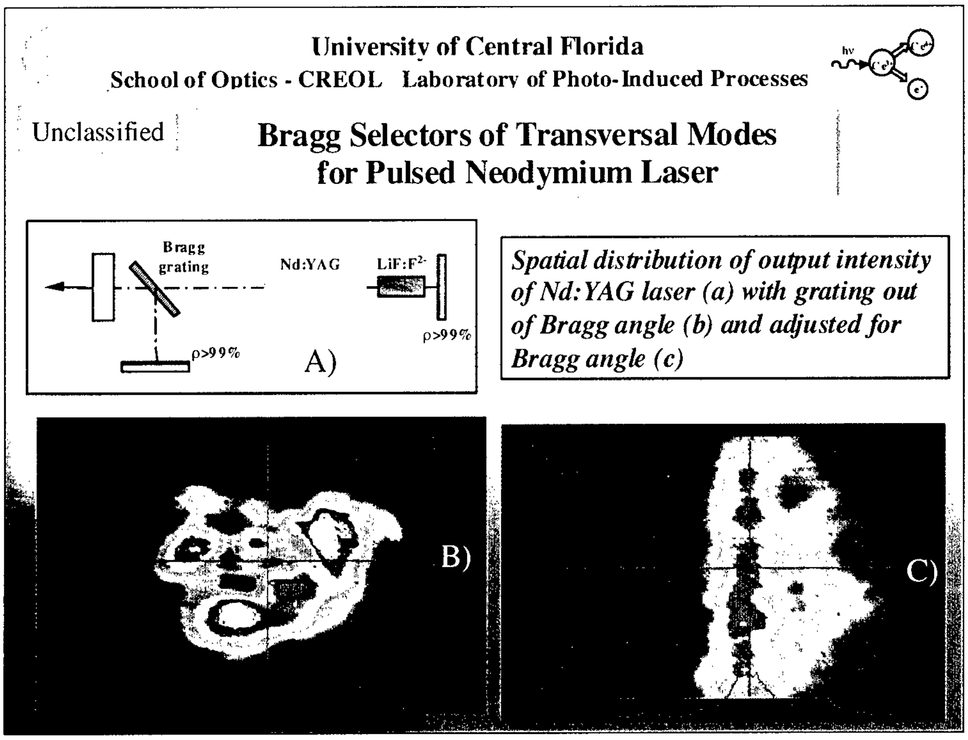
Scanning rate in configuration of the regular compact disc can be up to 10 kHz for a 3 mm diameter beam. Switching between recording tracks can be used for different wavelengths or for different regimes of scanning (upper figure).



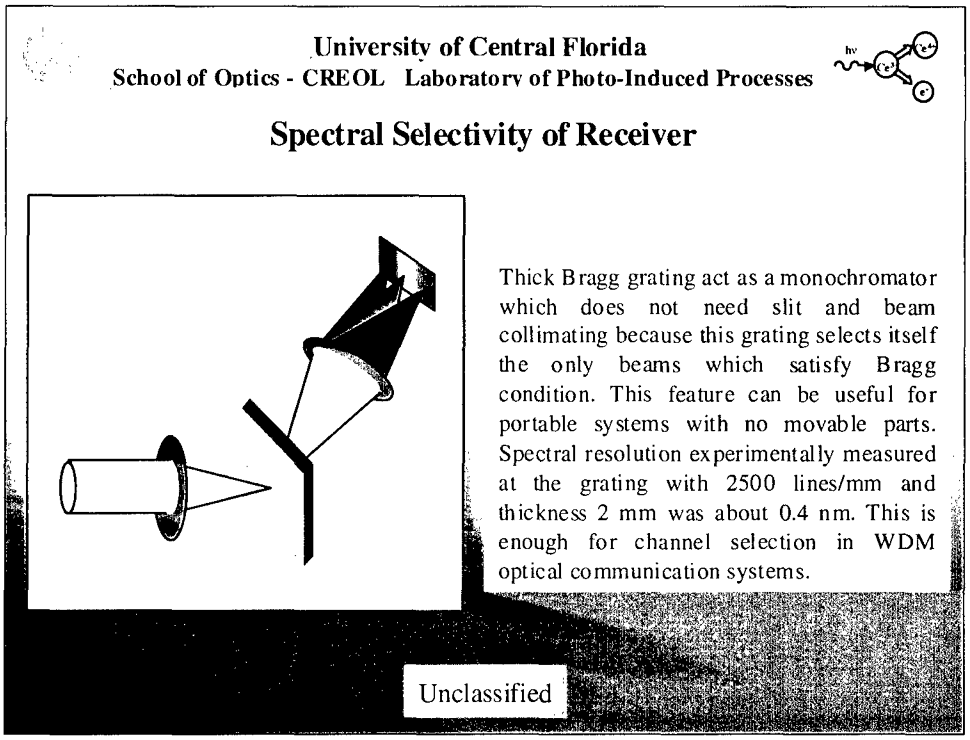
The combination of traditional scanning with matrix of holograms allows realization of high scanning rate and wide angular deflection. Recording of multiple gratings in the same volume, readable under different angles, allows switching between different regimes by rocking the matrix (lower figure).

Unclassified

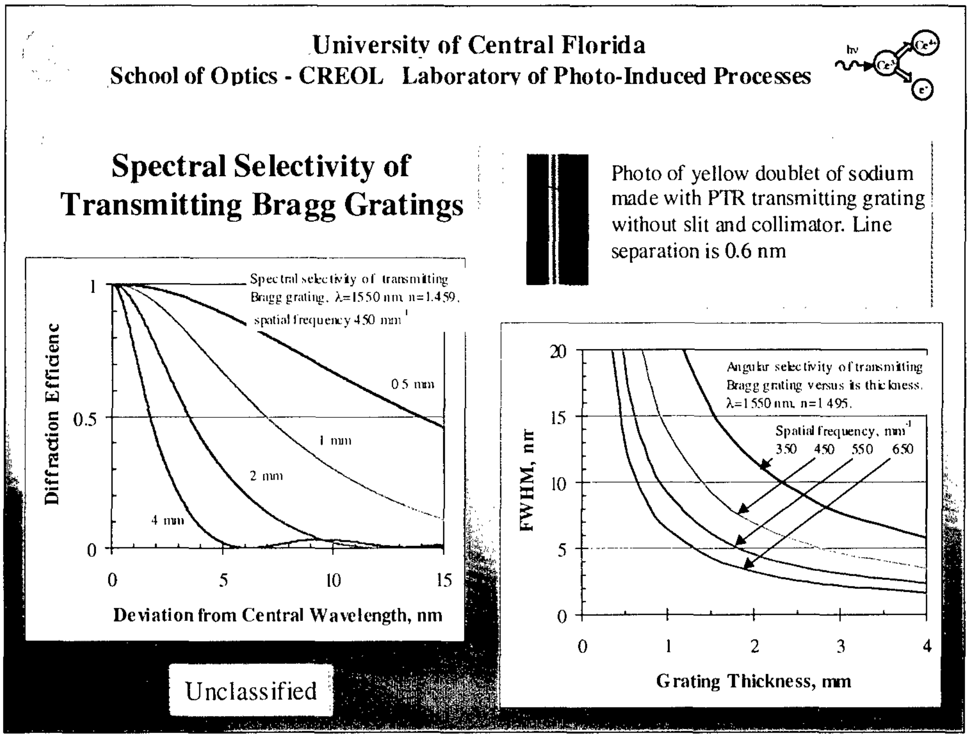
The use of a matrix of PTR Bragg gratings enables scanning the laser beam at arbitrary angles. This approach can be used as the sole one (upper scheme) or in combination with conventional electro-optical devices (lower scheme).



A pulsed Nd:YAG laser shown in this figure was used for the study of intracavity mode selection. This laser had a totally reflecting back mirror. Passive Q-switching was produced by a γ-irradiated single crystal of LiF with F^{2-} color centers. Output coupling was via a transmitting PTR Bragg grating while the diffracted beam was retroreflected by a dielectric mirror. In this case, the efficiency of the output coupler was tuned by the diffraction efficiency of the Bragg grating. It was found that stable laser oscillation could be observed with such construction of a resonator. To check the original properties of this particular resonator, the grating was turned off the Bragg angle and the front mirror was placed on the axis of the resonator. A near zone intensity mapping of the profile of this laser beam is shown in Fig. (B). One can see irregular oscillation with several hot spots because the resonator was made too short for selection of a single transverse mode. Fig. (C) shows a near zone mapping of the same laser with the PTR Bragg grating placed in the resonator. The intensity profile was reduced by a factor of 4 in the direction of the grating vector compared to the original laser resonator indicating that much lower order modes having much reduced divergence were selected. This figure shows that a thick Bragg grating is a very efficient mode selector in a laser resonator and therefore is a powerful tool for a high-energy single-mode laser design. It should be noted that no laser-induced damage, no nonlinear effects, and no fading of the grating were detected after its use for about one month.



Spectral selection of a target can be achieved by the use of PTR glass. A resolution of 0.4 nm can be attained with a 2 mm thick grating. No monochromator with slits and collimators are needed. A portable spectrometer for selected wavelengths with subnanometer spectral resolution with no moving parts looks very promising. Recording of multiple gratings in the same volume allows detection of several spectral lines without tuning.



The spectral selectivity of Bragg gratings in PTR glass can be varied from parts of a nanometer to several tens of nanometers. One can see the photo of the sodium doublet with 0.6 nm separation between the lines. It should be noted that no slits and no collimators were used in making this photograph.

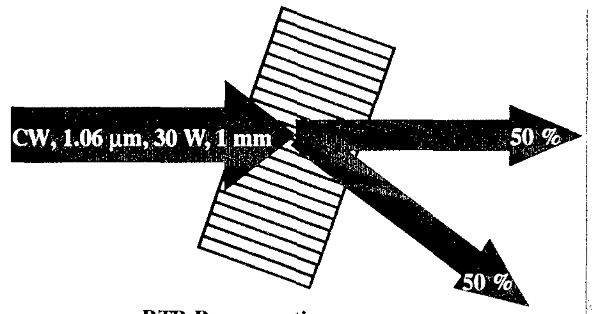
University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

APPLICATIONS TO HIGH POWER LASERS

Unclassified

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

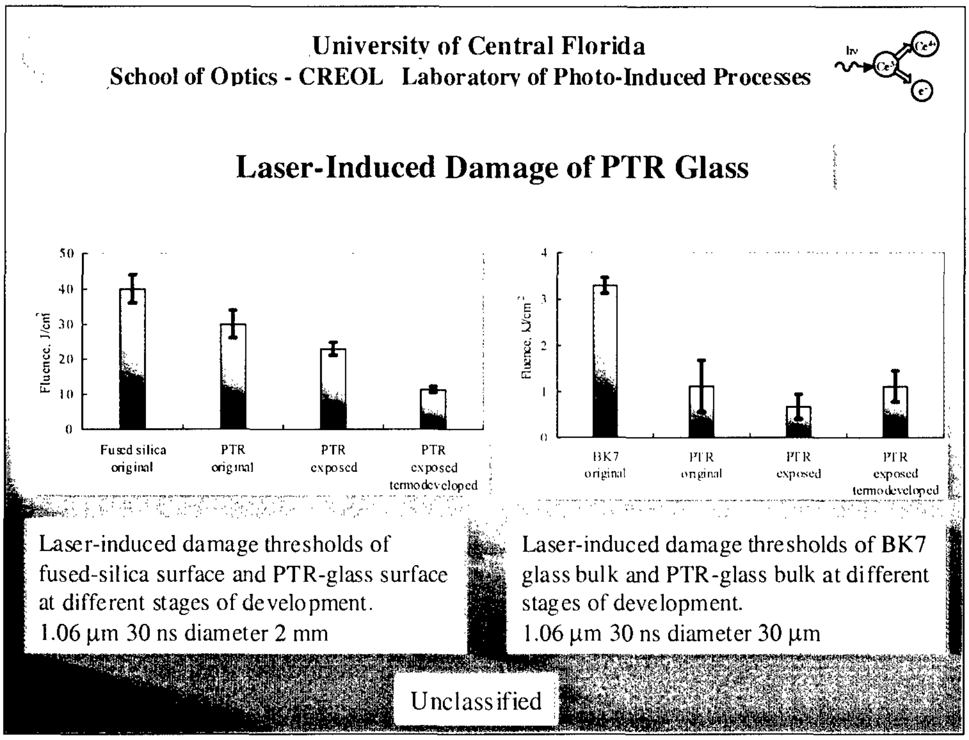
Unclassified **PTR Bragg Grating Test under High Laser Power**



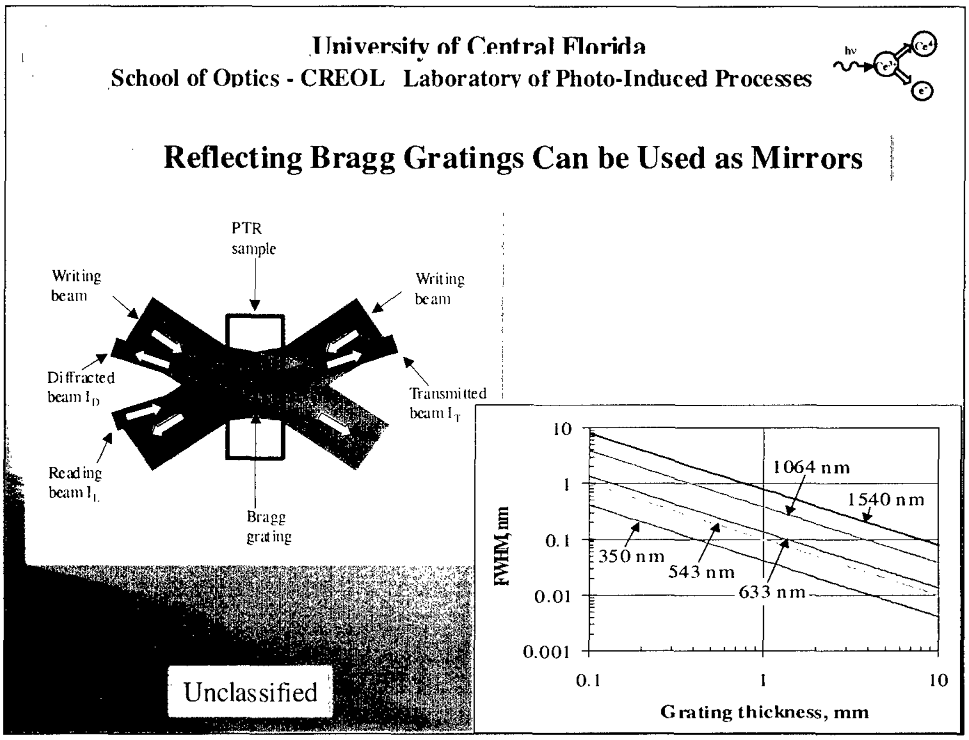
PTR Bragg grating

Transmitting Bragg grating in PTR glass (1000 lines per mm, 1.5 m thick, 50 % diffraction efficiency) was tested in the beam of CW YAG:Nd laser at 1.06 μm with 3 kW/cm² for 30 min. No laser-induced damage, no thermal lens, no Bragg angle shift, and no significant heating were observed. Detailed measurements will be performed in future.

Transmitting PTR Bragg gratings with about 50 % diffraction efficiency at 1.06 μm were tested at Lambda Physics Corporation using a cw YAG:Nd laser beam producing 30 Watts into a 1 mm diameter beam. No laser-induced damage, no thermal lens, no Bragg angle shift, and no detectable heating was observed. No attempt was made to optimize the glass or recording technology from the point of view of minimizing induced absorption in the near IR region. However, it is clear that this test indicates that PTR Bragg gratings should be useful in high-power IR laser systems.



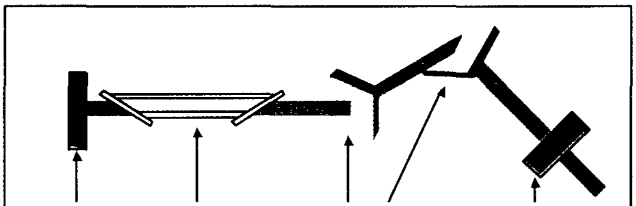
The laser-induced damage threshold of PTR glass was measured at the University of Rochester's Laboratory for Laser Energetics. It was found that exposed and developed PTR glass has a damage threshold for a 30 ns pulse of about 15 J/cm^2. This value is about 30 % of that for the best fused silica used at the Omega facility. So, PTR diffractive components can be used in high-peak-power laser systems.



Reflecting Bragg gratings can be recorded in PTR glass if the planes of the constant refractive index are parallel to the surface of the glass plate. A reflectivity above 90 % of the theoretical value was achieved for both visible and near IR regions. Achieved thicknesses of Bragg mirrors ranged between 2 and 3 mm. This means that spectral selectors with bandwidths from 0.01 nm in the UV to 0.2 nm in the near IR are achieved. The experimental values of the spectral widths were about 20 % greater than the theoretical values.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Selection of Transversal and Longitudinal Modes in a Laser



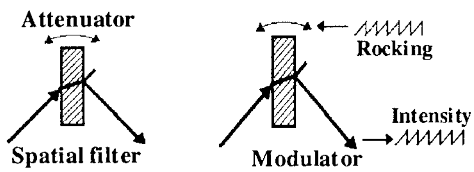
High laser damage threshold, low losses and high diffraction efficiency of Bragg gratings in PTR glasses can be used for mode selection in different types of lasers. This angular selector acts similar to a spatial filter but it is not necessary to focus beam to achieve filtering. Reflecting gratings have narrow spectral band and can be used for longitudinal mode selection instead of prisms and interferometers.

Unclassified

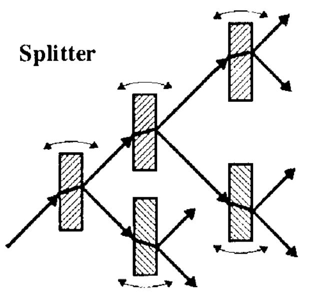
The placing of transmitting and reflecting PTR Bragg gratings in the laser resonator produces a strong selection of transverse and longitudinal modes. It is important to note that this spatial filtering in laser systems is used and is successful only because no conventional angular filters can be found in the market. The difference between different transverse modes is in the angular space and is the reason why angular filtering of transverse modes looks very promising. The spectral selectivity of Bragg mirrors in not enough to provide single frequency operation. However, it could be a powerful tool for the elimination of the periodicity of such highly selective elements as a Fabry-Perot interferometer.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Beam Splitting, Attenuation and Intensity Modulation



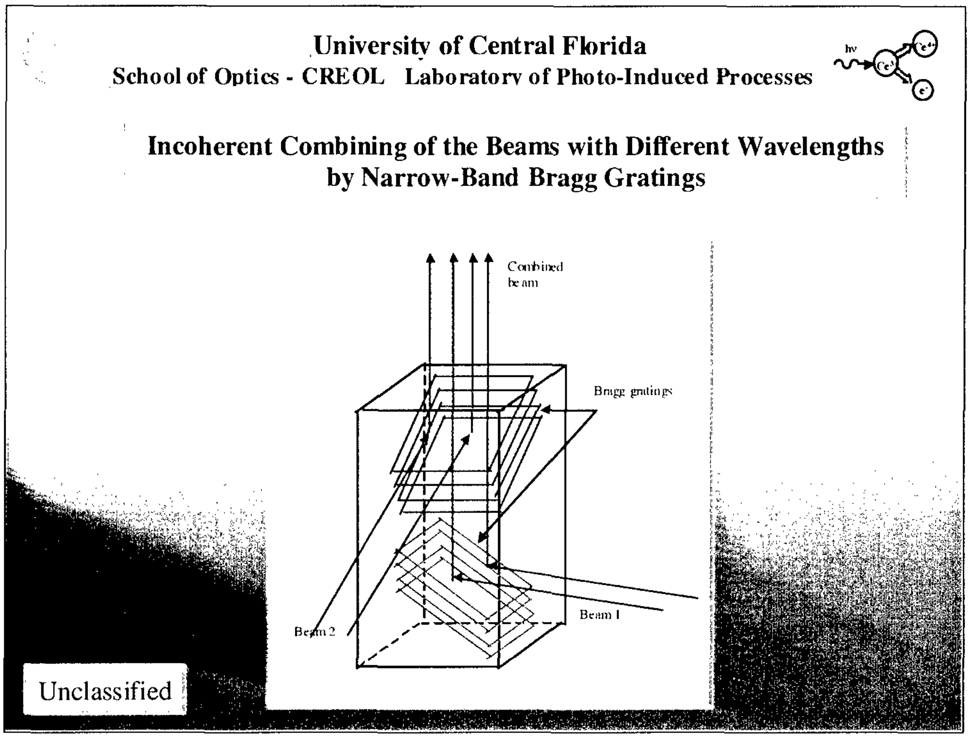
Low losses, high diffraction efficiency, low sensitivity to polarization, and sharp angular dependence of diffraction efficiency of gratings allows the fine gradual attenuation with the uniform attenuation in diameter and simultaneous cleaning the beam like a spatial filter.



The feature of Bragg grating to split beam to components with the same polarizations allows beam splitting with stepless ratio of intensities. Finally, this approach can give arbitrary number of beams with arbitrary desirable intensities and the same polarization. It is clear that the gratings rocking can produce a system with variable splitting ratio.

Unclassified

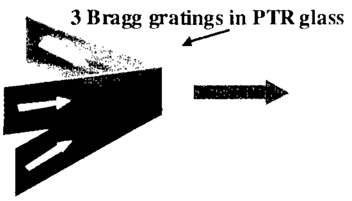
PTR glass will enable high energy laser designers to achieve the functions of beam splitting, attenuation, and modulation as shown in the viewgraph. The rotation of the Bragg grating over several angular minutes can result in the gradual reduction of the transmitted or diffracted intensities. This means that this element can serve as a beam splitter, channel equalizer and amplitude modulator. The combination of several gratings gives an opportunity to produce the beam splitter with an arbitrary number of channels and with arbitrary splitting ratios. MEMS devices could be used to drive the small angular rotation of these that are needed to make these modulators.

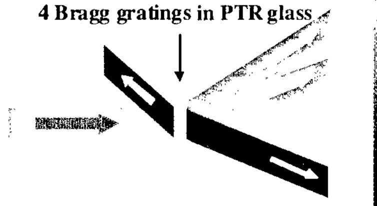


This figure illustrates how PTR glass should enable a designer to combine two beams from two different lasers into one beam. This is called incoherent beam combining. Coherent combining should also be achieved with this technology.CREOL currently has an effort sponsored by AFOSR and AFRL/DE to demonstrate incoherent beam combining of two 100W cw lasers in the manner shown in this viewgraph.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Multiplexing and Beam Diagnostics



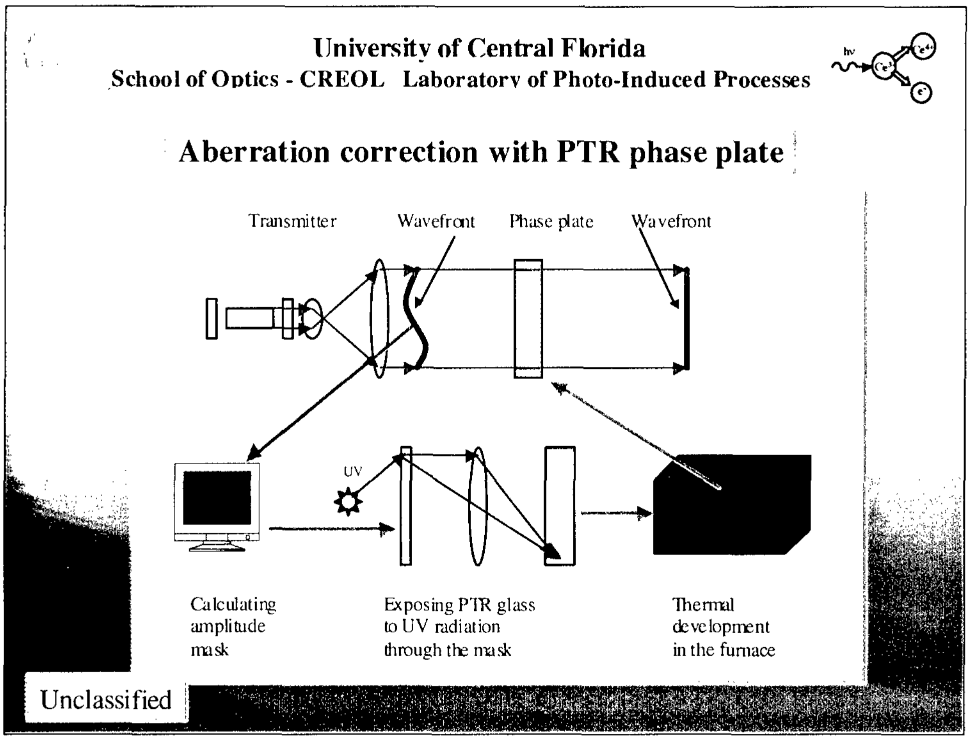


Recording of several Bragg gratings with high diffraction efficiency in the same volume of glass allows superposition or dividing of beams with different wavelengths. It is important that thick transmitting holograms in PTR glasses show high angular selectivity down to 0.2 mrad and can be used for pointing the target. Reflecting holograms can be used for wavelength division better than 0.1 nm.

Low losses and small scattering in PTR Bragg gratings allow the writing of several holograms with very small diffraction efficiency (down to 0.01 %), which contain all information of the original beam. High level of laser induced breakdown threshold allows application for the beam diagnostics of powerful lasers. It is important that holograms can be written in the regular optical element (lens, prism, etc.)

Unclassified

One of the main features of PTR glass is its ability to record multiple gratinsg in the same volume. The natural restriction for this approach is the maximum value of induced refractive index that is necessary for phase pattern recording with low crosstalk. Diagnosis of a high power beam may be accomplished by writing a weak grating in a piece of PTR glass that is used as another optical element in the optical train.



This illustrates how PTR glass can be used to correct aberrations or phase errors in an optical system. A mask is made of the aberration, and the conjugate of this is used to make the PTR glass phase plate. Insertion of the phase plate in the optical train will then correct for the aberration enabling "eagle-eye" vision to be built into the system.

University of Central Florida
School of Optics - CREOL Laboratory of Photo-Induced Processes

Unclassified

Conclusions

- Volume diffractive gratings have been fabricated in **photo-thermo-refractive (PTR) glasses** with absolute diffraction efficiency ***above 90 %*** for the spatial frequency up to ***10000 mm^{-1}***.
- Exposed and developed grating is not sensitive to optical radiation and stable up to ***400°C.***
- Angular selectivity of transmitting gratings down to ***0.5 mrad*** and spectral selectivity below ***1 nm*** were shown.
- No laser-induced damage, no thermal lens, no Bragg angle shift, and no significant heating were observed in PTR Bragg grating under 30 min. illumination of ***3 kW/cm^2*** at 1064 nm
- Laser-induced damage threshold for 30 ns pulses is about ***15 J/cm^2***
- This opens the way to a new class of rugged, low cost, insensitive optics

In conclusion, through BMDO support we have produced a new optical material which will enable the DoD to have angular filters, mode selectors, mirrors, beam splitters, beam combiners, attenuators, and other elements made from silicate glass having high laser damage threshold. This opens the way to having a new class of rugged, low cost, insensitive optics.